Composite Development & Applications for RLV Tankage

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Abstract

The development of polymer composite cryogenic tanks is a critical step in creating the next generation of launch vehicles. Future launch vehicles need to minimize the gross liftoff weight (GLOW), which is possible due to the 28%-41% reduction in weight that composite materials can provide over current aluminum technology. The development of composite cryogenic tanks, feedlines, and unpressurized structures are key enabling technologies for performance and cost enhancements for Reusable Launch Vehicles (RLVs). The technology development of composite tanks has provided direct and applicable data for feedlines, unpressurized structures, material compatibility, and cryogenic fluid containment for highly loaded complex structures and interfaces. All three types of structure have similar material systems, processing parameters, scaling issues, analysis methodologies, NDE development, damage tolerance, and repair scenarios. Composite cryogenic tankage is the most complex of the 3 areas and provides the largest breakthrough in technology. A building block approach has been employed to bring this family of difficult technologies to maturity. This approach has built up composite materials, processes, design, analysis and test methods technology through a series of composite test programs beginning with the NASP program to meet aggressive performance goals for reusable launch vehicles. In this paper, the development and application of advanced composites for RLV use is described.

1.0 INTRODUCTION

Lockheed Martin Space Systems Company- Michoud Operations (Michoud Operations) is a world leader in large cryogenic tank technology. Michoud Operations has fabricated external tanks for the Space shuttle for over 25 years. For X-33, Lockheed Martin VentureStar, X-34, and other future launch vehicles, Michoud Operations has used its expertise to make the required cryogenic propellant storage and handling systems. Composite hardware produced by Michoud Operations comprises the nose cone on the external tank on every space shuttle launched since January 1998.

1.1 **Launch Vehicle Configurations and Composite Structures:** Most of the structure in a launch vehicle is made up of propellant storage, support structures, and propellant lines. To reduce the weight of the vehicle's structure and therefore increase the available payload carrying capacity, the largest weight savings available are found in these structures. The mass fraction (ratio of structural weight to gross liftoff weight) of the next-generation of launch vehicles must be reduced significantly from that of current launch systems to increase payload carrying efficiency. Reusability has emerged as a major criterion for new launch vehicles intended to reduce launch costs by making repeated orbital deliveries without extensive maintenance. Composite tanks, feedlines, and vehicle structures offer weight savings up to 41% in certain vehicle designs and therefore are critical technologies for making these vehicles a reality.

As seen in the conceptual drawing in Figure 1, a typical reusable launch vehicle's structure consists largely of the fuel tanks and systems needed to deliver fuel to the engines. The fuel tanks comprise the vehicle's primary load bearing structure while the propellant handling system consists of vent and pressurization lines for moving gasses, valves for controlling flows, and large propellant feedlines for delivering propellants to the engines.

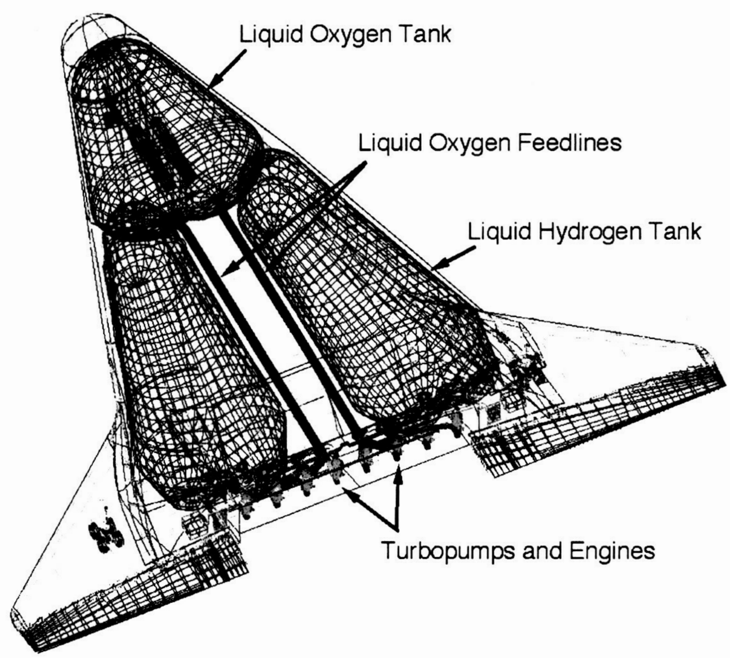

Figure 1: Typical internal layout of a reusable launch vehicle.

1.2 **Launch Vehicle Requirements:** In the most efficient liquid-fueled vehicle designs, the tankage and feedline systems must operate at –230°C (-423°F) for liquid hydrogen fuel, and -183°C (-297°F) for liquid oxygen. In the case of reusable vehicles, these systems may see temperatures in excess of +170°C (+250°F) during reentry. High temperatures are a concern for composite structures such as nosecones, fairings, intertanks, and aerodynamic surfaces, where temperatures as high as 515°C (960°F) occur during launch. Significant loads to the vehicle include boost acceleration, aerodynamic loading, and induced vibro-acoustic loads from the engines. Tank pressure is used to enhance vehicle structural stability, drive propellant into the feedline system at a controlled rate, and maintain the liquid cryogenic fuel. Typical launch vehicle propellant tanks pressures are 207 to 276 kPa (30 to 40 psi) for large vehicles and smaller vehicles operate at higher pressures as high as 520 kPa (75 psi) or more. High pressures require stronger and heavier tanks, so lower tank pressure is preferred.

1.3 **Composites Development at Michoud Operations:** For the past 20 years, Michoud Operations has developed composite structures for space launch vehicles. Select composite components built by Michoud are listed in Table 1 and can be seen in the collage photograph in Figure 2.

Program	Components Produced	Testing	Current Status
Space Shuttle External Tank	Nosecone	Full Flight Qualification	Flight Qualified/ deployed
	Pressurization Line Fairing	Full Flight Qualification	Flight Qualified/ deployed
	Intertank Access Door	Full Flight Qualification	Flight Qualified/ deployed
HyTOP Rocket	Composite Intertank, 6' Diameter	Tested to failure, cryo end fittings	
VentureStar RLV Development	3' diameter Liquid Hydrogen tank	13 LH2 Cycles	Ground Test Only
	17' Dual Lobe Liquid Hydrogen tank	78 LH2 Cyles	Ground Test Only
	GTDP Dual Lobe Liquid Oxygen Tank	Not Completed	Incomplete
X-33	35" Composite LH2 Tank Coverplates	Full Flight Qualification	Flight Qualified/ Delivered
	35" Composite LH2 Tank Coverplates	Full Flight Qualification	Flight Qualified/ Delivered
	35" Composite LH2 Tank Coverplates	Full Flight Qualification	Flight Qualified/ Delivered
	35" Composite LH2 Tank Coverplates	Full Flight Qualification	Flight Qualified/ Delivered
Independent Development	17" Dia Composite Feedline	Tested to ET Flight Requirements	Testing Successful, Development
X-34	22" Diameter LO2 Tank Coverplates	1 LN2, 30 LO2 cycles	Tested with pathfinder
	54" Diameter Liquid Oxygen Tank (Flight)	Partially Complete	X-34 cancelled prior to completion
	54" Diameter Liquid Oxygen Tank (Proof)	1 LN2, 30 LO2 cycles	Phase 1 testing complete
	X-34 Composite Fuel and Vent Lines	1 LN2, 30 LO2 cycles	Tested with pathfinder

TABLE 1: Major Composite Components Developed at Michoud Operations

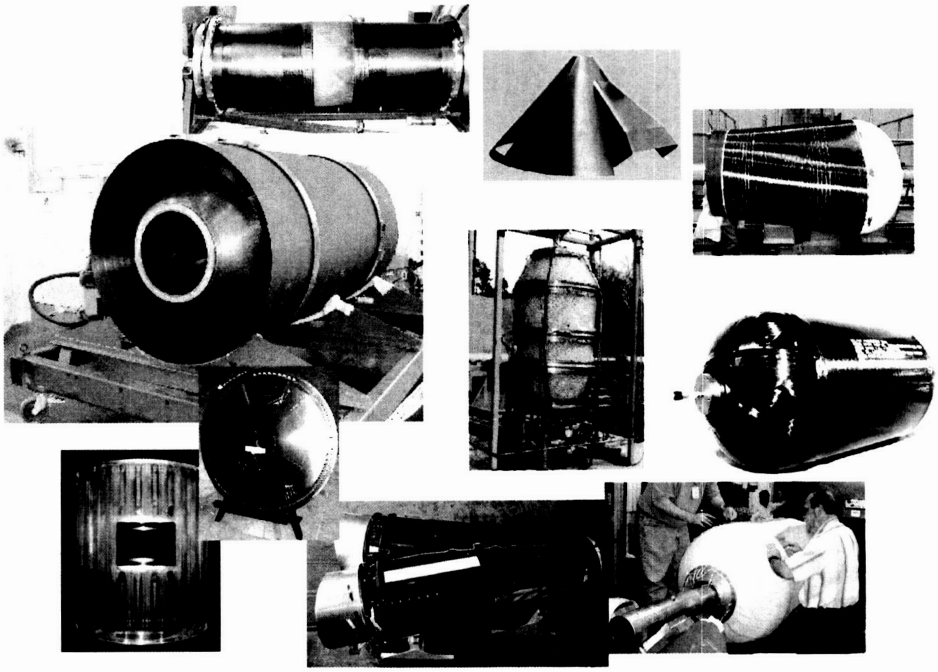

Figure 2: Composite Hardware Developed at Michoud Operations.

2.0 CRYOGENIC STRUCTURES

2.1 **Cryogenic Structures Development:** Composite materials offer the potential for 20% to 40% weight savings over metal tanks and structures on launch vehicles. Weight savings of this magnitude are an enabling technology for single stage to orbit vehicles, such as the Venture Star, Figure 3. Michoud Operations has pioneered the use of composite materials for use in cryogenic launch vehicle applications.

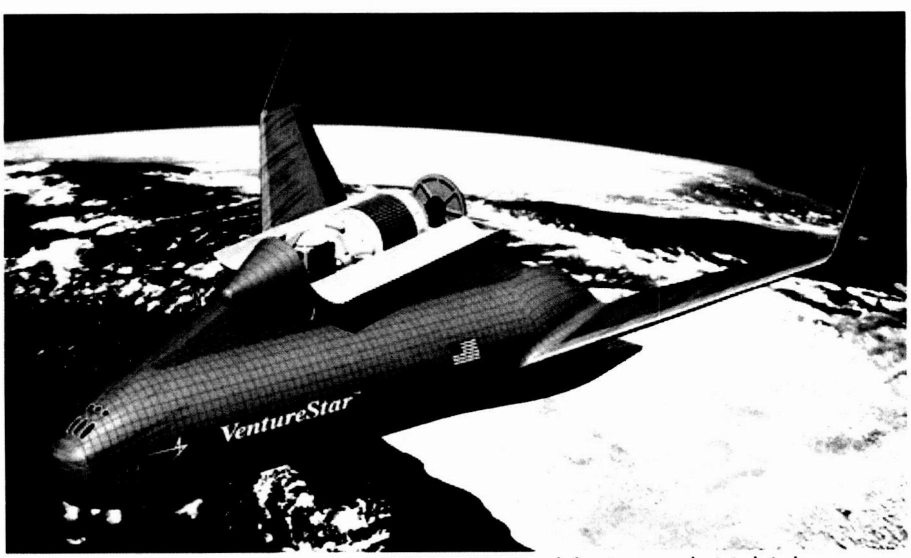

Figure 3: The Venture Star Reusable Launch Vehicle

2.1.1 **Cryogenic Tanks:** Cryogenic tanks are a particularly difficult application for composite materials. Not only must laminates used in these applications be very structurally efficient, they must also contain extremely volatile cryogenic propellants (typically liquid hydrogen and liquid oxygen). Two of the primary issues for tanks operating in these environments are: (1) cryogen containment, and (2) chemical compatibility, particularly with liquid oxygen.

2.1.2 **Cryogen Containment:** There are two concerns with respect to cryogen containment, one is permeation, or the diffusion of the fluid molecules through the composite laminate, and leakage, which is the flow of gas or liquid through defined leak paths in the composite material. With respect to permeation, the diffusion rates through laminates without microcracking or internal defects are very low and are not a concern for most applications. The larger concern is tank leakage.

To meet the containment requirements for most composite propulsion system applications, a composite material must be free from defects, which cause leak paths through the laminate. Potential leak paths include interconnecting porosity, mechanical damage resulting in through cracks, delamination, and the accumulation of microcracks between the resin and fibers.

With respect to porosity, studies have shown even small levels of local porosity can cause significant leakage; therefore, laminates used for containment have to be virtually porosity free. Impact damage, which typically creates a local area of cracks through the thickness, is also a significant leakage concern. Impacts as low as 5 ft-lbs. have been shown to produce leak paths in toughened epoxy matrix carbon fiber reinforced composites unless careful tooling and manufacturing approaches are used, similar to those used to protect space flight hardware for the space shuttle and other space flight hardware.

Microcracking is another significant issue for composite materials in cryogenic tanks. Because of the large differential in the Coefficient of Thermal Expansion (CTE) between the resin and fiber in carbon reinforced composites, there are significant internal tensile stresses built up in the resin matrix when the composite is cooled to cryogenic temperatures. Conventional resin systems used in composites also become brittle and their available strain to failure decreases significantly. In many cases, the reduced strain capability combined with the thermal strain from the CTE difference will cause microcracking in the laminate. Laminates for use in cryogenic propulsion systems must not only withstand the extreme thermal stresses and strains, they must also withstand the added burden of mechanical stresses and strains from pressure and external loads applied to the tank without having their performance compromised by microcracking. In most applications, the materials must withstand this combination of mechanical and thermal strains over multiple operating cycles.

2.1.3 **Liquid Oxygen Compatibility:** In addition to the containment requirements, composites for use in liquid oxygen systems must also be chemically compatible with liquid oxygen. Composite materials do not currently meet the industryaccepted requirements for oxygen compatibility, which have been developed to encompass the most extreme propulsion environments. However, the environments for large structures such as cryogenic tanks are much less severe than those for smaller components, such as valves; a blanket requirement based on the most extreme conditions in a vehicle will often rule out materials based on a single small component's requirements.

To address problems with the previous industry standard approach, Michoud Operations has worked in conjunction with NASA and developed an alternative approach to liquid oxygen compatibility. A process flow diagram of this new approach is shown in Figure 4. Michoud Operations has successfully developed and verified materials for liquid oxygen tank applications according to this approach for use on programs such as the X-34 liquid oxygen tank and the liquid oxygen feedline development program. Testing for liquid oxygen compatibility includes standard tests, such as mechanical impact in liquid oxygen, mechanical impact in gaseous oxygen, high velocity particle impact, friction, and pyrotechnic shock. To address system level concerns for structures and assemblies used in liquid oxygen, larger scale tests have also been conducted.

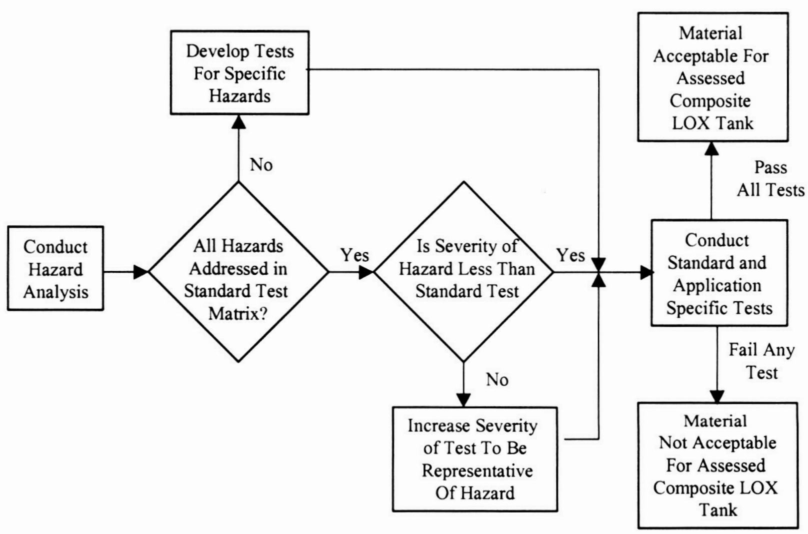

Figure 4: Composite LOX Tank Verification Process

Large scale liquid oxygen compatibility testing has been performed using full scale subassemblies as well as complete tanks and system elements built specifically for this purpose. Subassembly level testing has included taking full scale component sections and joints and cycling them to flight loads then pulling them to failure while immersed in liquid oxygen. These subassembly tests verified liquid oxygen reactions do not occur with our materials, even in the event of catastrophic structural failure. We have completed vibration testing, shown in Figure 5, with small tanks with various kinds of debris (bolts, metal shavings, etc.) with liquid oxygen fill levels of 30%, 50%, and 90% without causing liquid oxygen reactions.

Figure 5: Vibration Testing of Composite Tank Filled With Liquid Oxygen

A specially designed pressure drum tested with liquid nitrogen verified the material system developed for liquid oxygen compatibility was capable of meeting permeation requirements. This 17" inner diameter drum had the same lay-up used later on the X-34 tank and had full flight-level strains applied under pressure. After testing, the drum specimen was sectioned to make specimens for examination. This modular testing approach makes it possible to cheaply evaluate the cryogenic cyclic behavior of a material system in the identical strain state it will encounter in use. Unlike plate or cruciform specimens, the desired strain state for a drum specimen is reached in a large area, making it possible to produce a large number of specimens. Any desired strain ratio between the axial and longitudinal directions in the drum can be produced by applying pressure along with applied loads from the end fittings.

Full scale tank testing for the X-34 program moved forward to testing a finished X-34 tank for 30 cycles with liquid oxygen with full pressure. The X-34 tank is the first completed flight qualification series for a composite tank including joints, seals, composite manhole covers, valves, composite ducts and fuel lines, and internal dome features. This testing proved reusable composite liquid oxygen tanks are both feasible and practical. The X-34 test tank is seen in Figure 6.

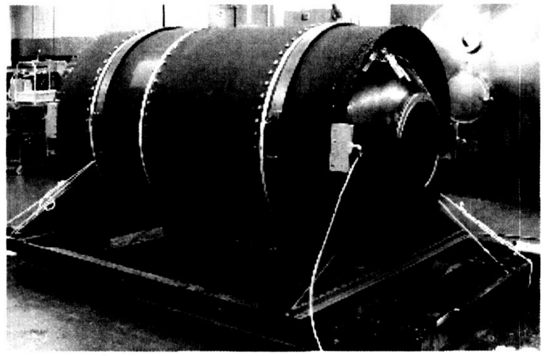

Figure 6: The X-34 Composite Liquid Oxygen Tank.

2.2 **Specific Cryogenic Tank Development Programs:** Michoud Operations has successfully carried out several development programs which have demonstrated the potential for using composites for cryogenic tanks. This development has placed Michoud Operations with unique experience and capability in the design, manufacture, and test of cryogenic composite tanks.

2.2.1 **3 ft. x 6 ft. Liquid Hydrogen Tank:** Figure 7 shows a 3 ft. x 6 ft. liquid hydrogen tank which was successfully tested with liquid hydrogen to material strain levels equivalent to those required for flight hardware. This tank was fiber placed with prepreg tape and autoclave cured. This was the first fiber- placed composite cryogenic tank. The tank completed 13 cryogenic pressure cycles using liquid hydrogen. After testing, coupons cut from the tank wall laminate for inspection indicated limited microcracking in some of the plies consistent with the pre-test analytical predictions. This tank successfully demonstrated composite laminates could be used at high strains to contain liquid hydrogen during repeated cryogenic cycles.

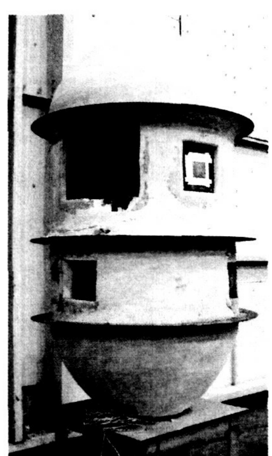

Figure 7: The 3 ft. Diameter LH2 Tank After Testing

2.2.2 **HyTOP Hibrid Rocket Intertank:** One of the critical structures in a launch vehicle is the series of support skirts which support the tanks in the vehicle.

Intertanks are a double-ended version of these skirts which forms a support between two tanks and thus are a major vehicle component. Michoud Operations developed a composite intertank, seen in test in Figure 8, for the Hytop hybrid rocket. The completed intertank was tested to 112% of its design load, or 4000 lb. per inch of circumference with cryogenic temperatures applied at the end as would be the case in flight. The part was then tested to failure, where it withstood 223% of its limit load before failure. The technology to build high performance structures similar to this intertank makes large all-composite vehicles practical as well as weight-efficient.

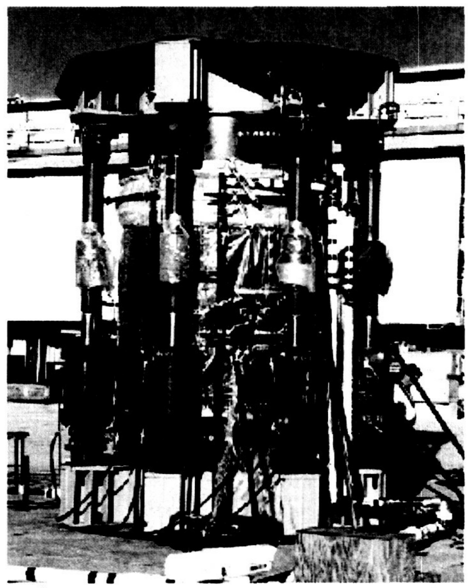

Figure 8: The 6 ft. X 7 ft. HyTOP Composite Intertank During Cryogenic Test

2.2.3 **10 ft. x 17 ft. Dual Lobe Cryogenic Composite Tank:** The tank seen in Figure 9 is the 10 ft. x 17 ft. dual lobe cryogenic composite tank developed as part of the X-33/ VentureStar single stage launch vehicle program. This was the first multi-lobe hydrogen tank to successfully complete realistic pressure testing. This tank, see in the test stand in Figure 10, completed a total of 78 LH2 cryogenic cycles at NASA Stennis Space Center and subsequent testing at Nasa Glenn Research Center with no detectable leakage in the membrane areas of the tank. This testing not only included pressurized fills with liquid hydrogen, but also included propellant densification testing where super-cooled liquid hydrogen was circulated through the tank to further chill and densify the liquid hydrogen in the tank to make it possible to put more mass of propellant in the same volume. After testing, coupons cut out of the laminate indicated limited microcracking as predicted in a limited number of the plies, consistent with analytical predictions for microcracking.

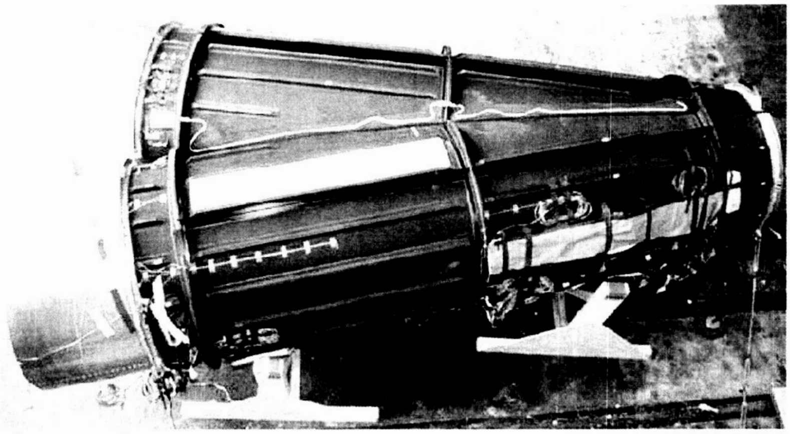

Figure 9: 10 ft. x 17 ft. Dual Lobe Cryogenic Composite Tank (Without Insulation)

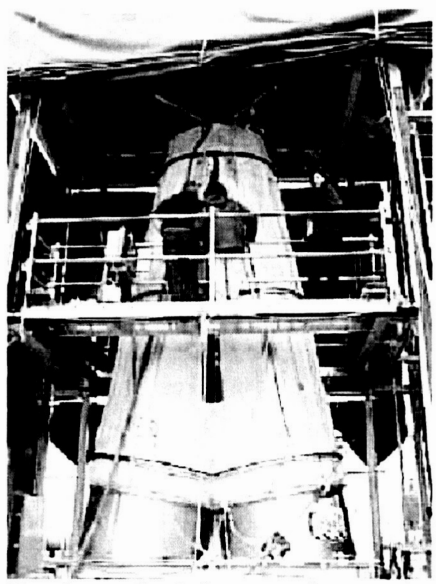

Figure 10: Cryogenic Testing of 10 ft. x 17 ft. Dual Lobe Composite Tank

The barrels for this tank were fiber-placed, Figure 11, using slit pre-preg tape and autoclave cured. The end domes were hand laid up and co-cured to the barrel skins. The stiffeners running along the barrels were hand laid up and autoclave cured separately before they were secondarily bonded to the tank skins.

Other successful demonstrations in the tank included the demonstration of a weight effective bolted joint between the lobes. This extremely strong joint made it possible to build the tank in halves before bolting it together with a seal running around the separation perimeter between the lobes. The bolted joint proved to have greater strength, better sealing capability, and lower weight than equivalent bonded joints. This joint was monitored during testing and showed no indication of hydrogen leakage.

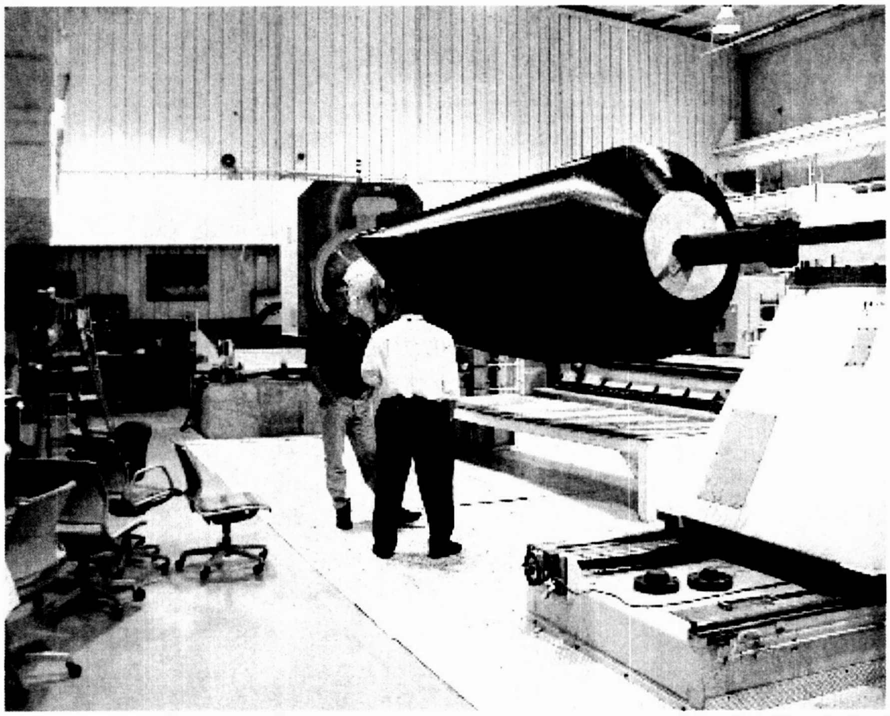

Figure 11: 10 ft. x 17 ft. Dual Lobe Cryogenic Composite Tank In Fiber Placement

The areas of highest concern for leakage from the tank were the discontinuities caused by bonded joints such as where the domes joined the barrel, or where the lobes curved over into tight radii to join the center septum. The tank did exhibit leakage at a few isolated areas where at typical manufacturing anomalies such as wrinkles. A thorough inventory of the tank laminate defects and leakage locations indicated conventional composite laminates with defects capable of passing typical inspections today would not meet the requirements for containment in a composite cryogenic vessel. Therefore, tank proof testing methods and repair techniques have been developed to ensure flight tanks meet leakage requirements.

2.3 **Semi Conformal Tanks:** Michoud Operations has completed pioneering studies comparing semi-conformal tanks such as the one seen in Figure 12 to multi-lobed tanks for fitting tanks into the complex shapes of single stage to orbit vehicles. These studies have shown this innovative design, which allows a pressure vessel to have flat or arbitrarily curved surfaces, can produce semi-conformal tanks as light as multi-lobe tanks on an equal volume basis. This research also indicated one of the enabling technologies in making weight-efficient semi-conformal tanks is the modified sandwich composite construction capable of performing at cryogenic temperatures developed by Lockheed Martin at Michoud Operations.

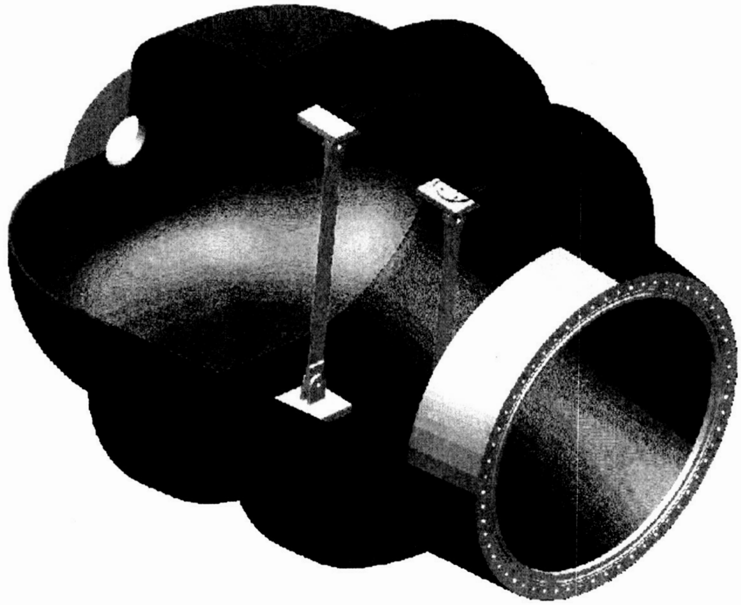

Figure 12: Semi-conformal Development Tank

2.4 **Propulsion System Components:** Composites have significant potential to reduce the weight of other propulsion system components, such as feedlines, coverplates, and secondary pressurization tanks. In these roles, composites face new requirements such as large point loads, handling by personnel, provisions for assembly and disassembly, and precision alignment of interfaces for other components.

2.4.1 **Composite Feedlines:** Composite Feedlines must not only meet all the technical challenges of cryogenic tanks, but to be weight effective, they must also have lightweight structural interfaces. Michoud Operations has developed and tested a 17" diameter by 4 ft. long composite feedline concept with integral composite flanges which is 25+% lighter than an all-aluminum alloy feedline. Figure 13 shows the composite feedline being tested under combined cryogenic, pressure, and axial load testing. This component was designed and tested to perform to the requirements for the 17" diameter liquid oxygen line used on the Space Shuttle External Tank. The External Tank liquid oxygen feedline is the largest line ever flown. The feedline successfully passed testing to 160% limit load with no leakage or failure.

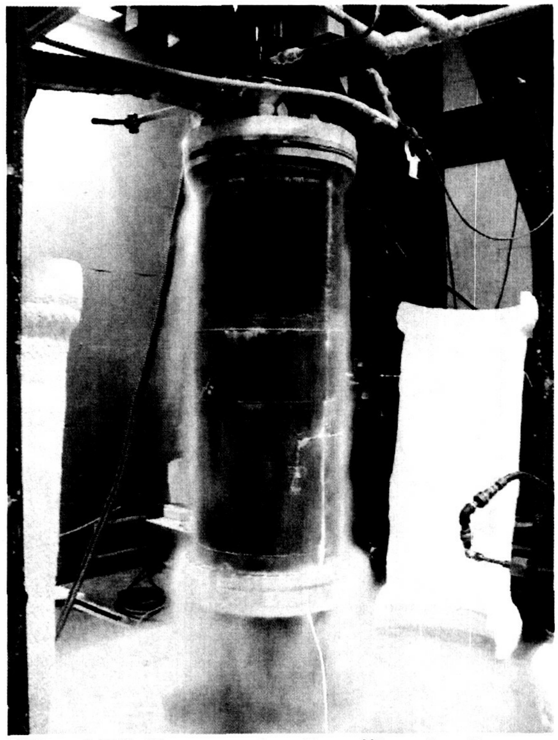

Figure 13: The 17" Composite Feedline in Cryogenic Test

2.4.2 **Composite Coverplates:** Composite coverplates present many challenging issues. One of the most difficult issues is maintaining clamp-up pressure in the bolts holding the coverplate on at cryogenic temperatures. Because composite laminates have very high coefficients of thermal expansion in the through-the-thickness direction, a typical laminate will lose all clamp-up force at cryogenic temperatures because of change in thickness of the laminate will be much greater than the change in bolt length for the same temperature change. Michoud Operations has developed and applied for patent on several technologies to effectively mitigate this problem.

Other issues with coverplates include effectively sealing the perimeter of the coverplate, sealing the many different penetrations in the coverplate, and reacting the significant structual loads input by the hardware mounted on the coverplate. Michoud Operations has developed and demonstrated several successful pass-through configurations capable of withstanding very high loads in cryogenic environments while maintaining a seal.
All of the key coverplate technologies were demonstrated in the coverplates for the X-33 LH2 cryogenic tank, Figure 14. For flight qualification, one coverplate underwent 47 cryogenic/pressure cycles with external loads, Figure 15, with no loss in clamp-up, no leakage in the major perimeter seal, and no leakage. At the end of testing, this same cover was cryogenically loaded to 50% overpressure with an additional 50% applied load and still did not leak. Four different coverplates were produced with five different pass-through configurations and all were

successfully acceptance tested for three cycles to 25% overpressure with liquid hydrogen and delivered.

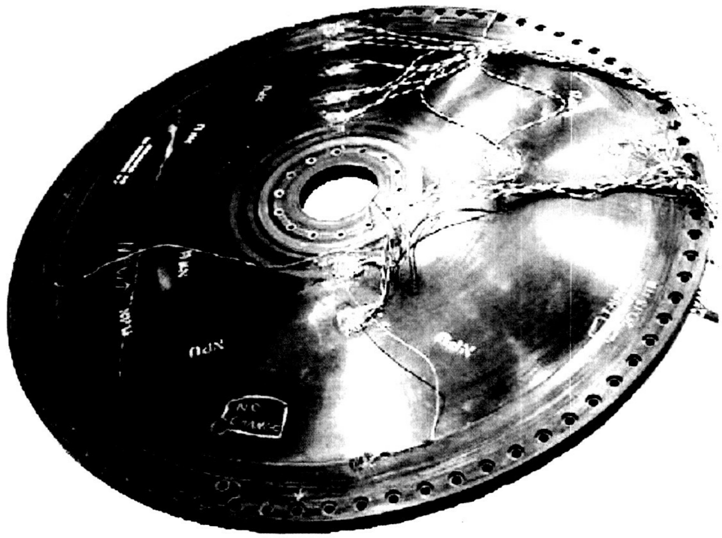

Figure 14: 35" Diameter Aft Composite Cover Plate

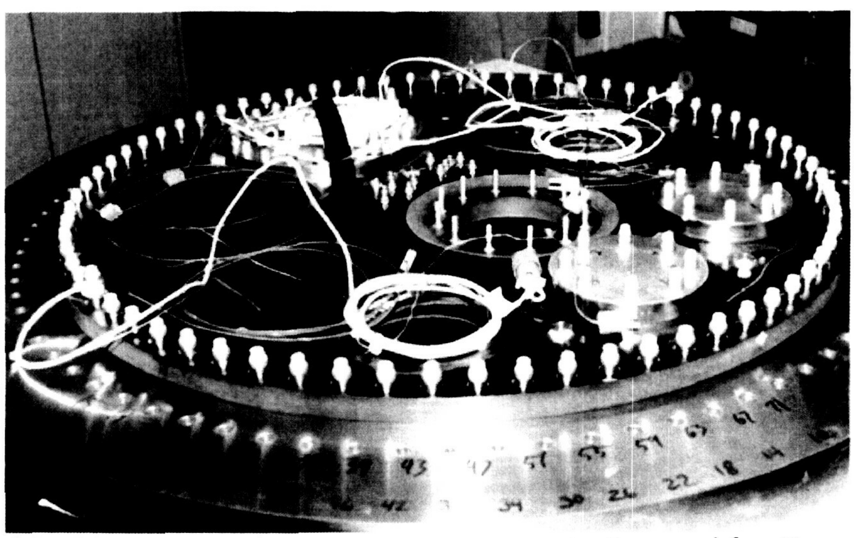

Figure 15: 31" Diameter Fwd Composite Cover Plate Prepped for Cryogenic Test

2.4.3 **Cryogenic High Pressure Tanks:** Several studies have shown significant weight savings by using heated helium pressurization for liquid oxygen tanks on liquid oxygen/liquid hydrogen launch vehicles. In this type of system, baselined for the X-33 launch vehicle and for the Venture Star reuseable launch vehicle, high pressure helium tanks are stored inside the liquid hydrogen tanks. The cryogenic cooling allows 1400% more helium to be stored in a given tank volume than would be available at room temperature. Helium from the tanks runs through a heat exchanger in the engines where the helium is heated and expanded to pressurize the liquid oxygen tank. Maximum weight efficiency for this type of system can be achieved by using composite over-wrapped tanks.

Michoud Operations has developed patented technology for composite overwrapped tanks with titanium liners which have been qualified for high pressure use in liquid hydrogen. In this testing, the tanks completed 50 complete cryogenic/ pressurization cycles, plus an additional 7 pressurization cycles at liquid hydrogen temperatures. The tank was then taken to 200% of operating pressure to verify margin. The tank was subsequently non-destructively inspected with laser holography and cut-up for examination. No evidence of cracking in the metal liner or delamination of the liner/overwrap interface or the composite laminate were found. Figure 16 shows the tank as completed.

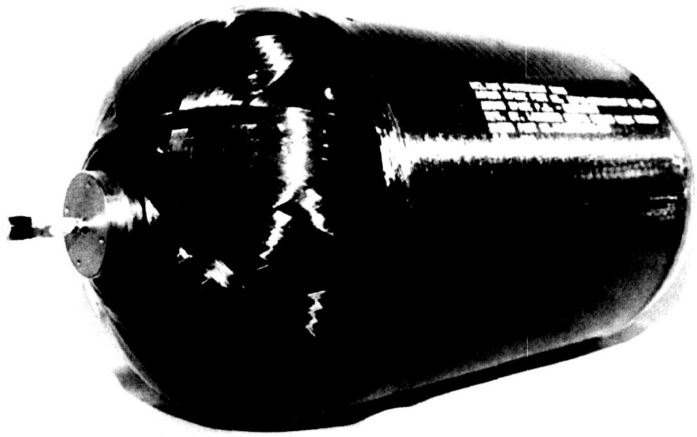

Figure 16: High Pressure Cryogenic Helium Tank

2.5 **Cryogen Containment Repair:** One of the key technologies required for implementing composites in cryogenic tanks is the ability to repair laminates. Repair techniques developed at Michoud Operations have proven effective in restoring containment ability to laminates with damage and defects which otherwise cause unacceptable leakage. These techniques were tested on coupons in combined cryogenic-load cycling before they were successfully employed on the X-33 LH2 tanks to repair leaks prior to testing. These repairs were shown to be effective in cryogenic tank pressure testing on the X-33 LH2 tank, Figure 17.

Figure17: Repair of X-33 LH2 Tank

2.6 **High Pressure Helium Tank for Satellite Applications:** Weight is critical for satellites, where structural mass trades for vehicle capability and launch cost. One of the most successful uses to date for high pressure tanks developed at Michoud Operations has been for long-term helium storage tanks used on the propulsion systems for A2100 series commercial satellites built by our sister company, Sunnyvale Operations.

The first of these tanks went into orbit in 1996, and at this time, six of these titanium lined composite over-wrapped tanks are in orbit aboard A2100 series satellites. These tanks, see in Figure 20, are rated for ten-year helium storage and have the highest tank storage efficiency rating of any high pressure tank of its size produced up to this time with a PV/W (burst pressure *volume/weight) volume efficiency of 1.45 million inches. When compared to typical aluminim lined COPVs which have PV/W of around 1 million inches for a 4950 cu. in. volume tank, the Michoud Operations tank is far more weight efficient. Michoud Operations has developed, flight qualified, and patented technology for the most weight efficient pressure tanks developed to date.

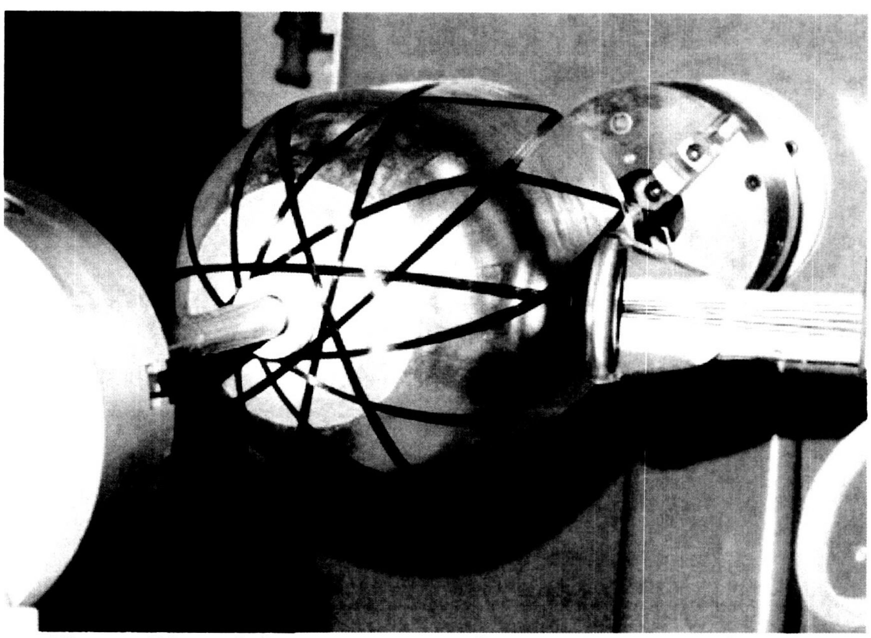

Figure 20: High Pressure Satellite Tank In Manufacture

2.7 **X-34 Liquid Oxygen Tank:** Michoud Operations has developed and built a composite liquid oxygen tank which was to be flown on an X-34 vehicle. This tank, seen in Figure 21, will be the first composite liquid oxygen tank ever flown and therefore represents the culmination of many different efforts by Michoud Operations over many years to develop the technologies needed to fly such a tank.

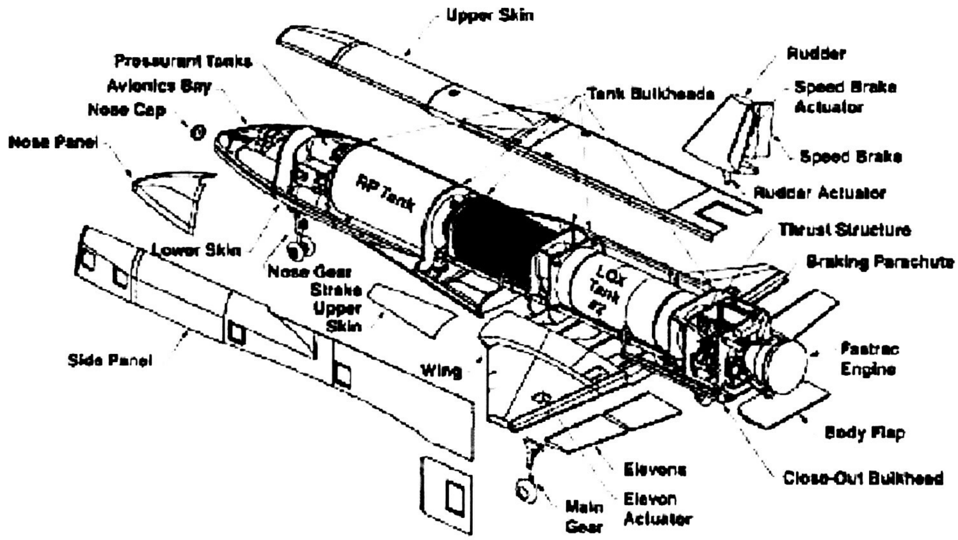

Figure 21: Schematic of The X-34 With The Composite Liquid Oxygen Tank

The X-34 composite liquid oxygen tank incorporates a large number of technologies developed at Michoud Operations including Lockheed Martin's proprietary liquid oxygen compatible materials, three sealing attachments, two types of reinforced dome joints, composite coverplates, composite liquid oxygen feedlines, and composite vent lines. As seen in the cutaway view in Figure 22, The X-34 liquid oxygen tank incorporates a large number of the features required for much larger liquid oxygen tanks. By testing the proof tank, seen in Figure 23, Michoud Operations and NASA demonstrated the maturity level composite cryogenic tanks have reached and their fitness for use in future launch vehicles.

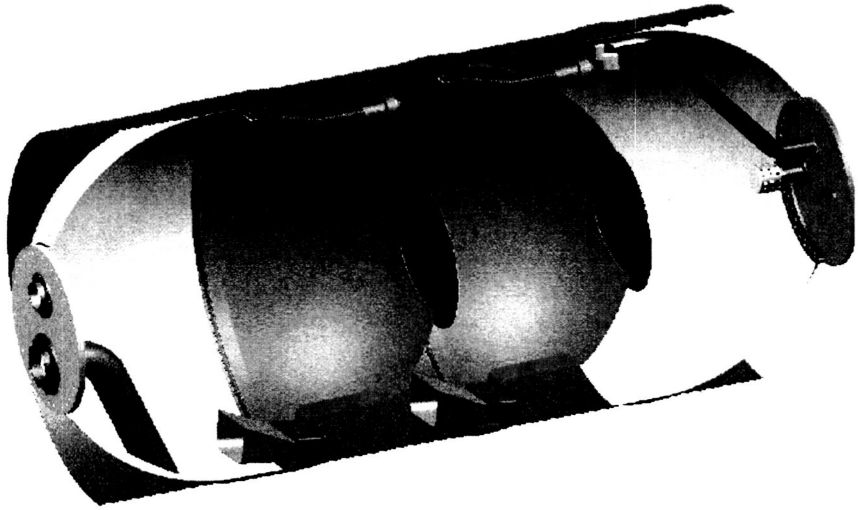

Figure 22: Schematic of The X-34 Composite Liquid Oxygen Tank

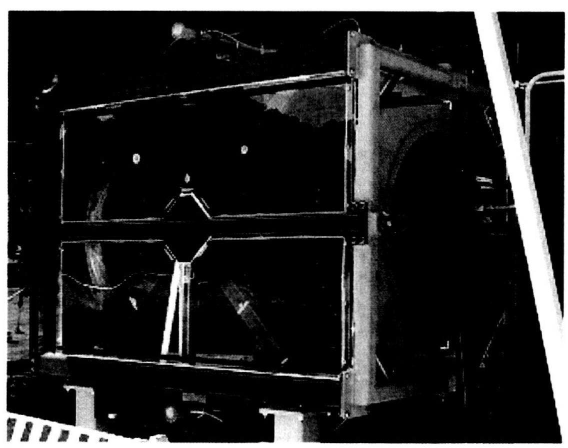

Figure 23: The X-34 Composite Liquid Oxygen Tank in Test

3.0 NCAM- THE NATIONAL CENTER FOR ADVANCED MANUFACTURING

The NCAM at Michoud Operations combines the talents and resources of industry, the government, and academic institutions to create the capability to build large composite structures. This effort includes installing the capability to fiber-place large composite structures as well as autoclave facilities for curing large components. The academic side of this venture will enhance analysis, design, research, and development capabilities to build new advanced structures. Research activities carried out by the NCAM facility will continue to develop capabilities to design new launch vehicles and large structures in the future. The facility development program, an example of which is seen in Figure 24 will continue to increase manufacturing capabilities at Michoud. The NCAM fiber placement machine can be seen in Figure 25 shortly after its installation at Michoud.

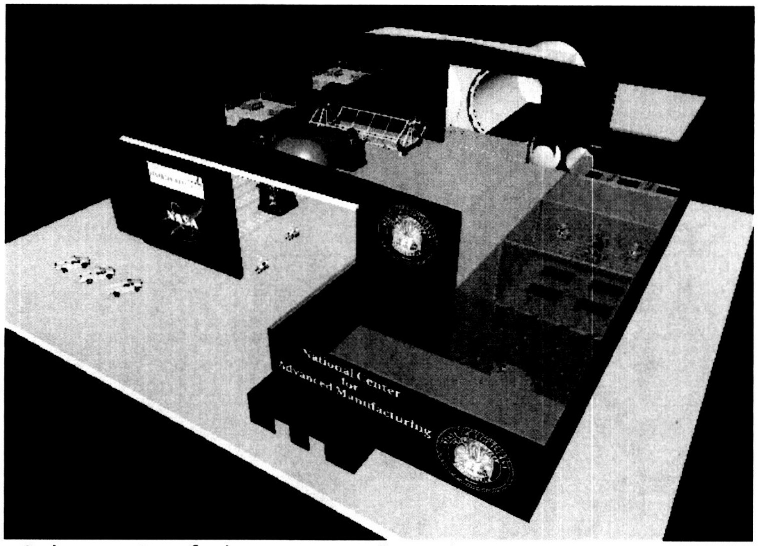

Figure 24: Schematic of The Large Fiber Placement and Autoclave Facility Being Installed at Lockheed Martin Space Systems Company- Michoud Operations.

Figure 25: The NCAM Fiber Placement Machine Installed at Lockheed Martin Space Systems Company- Michoud Operations with its first completed component.

4.0 SUMMARY

Research on liquid oxygen compatibility, cryogenic composite structures, high temperature composite structures, and liquid fuel delivery systems has been integrated to produce practical solutions for composite launch vehicles at Lockheed Martin Space Systems- Michoud Operations. Michoud Operations has followed a building-block approach and has produced many different types of tanks, components, and test articles for programs ranging from flight hardware for the space shuttle external to components for the X-33 and X-34 experimental vehicles. Testing on full-scale tanks, components, feedlines, and subcomponent test articles has demonstrated composite hardware designed and built by Michoud Operations can meet the most stringent operational requirements at cryogenic and elevated temperatures while also saving weight. The twenty-five years of experience Michoud Operations has in developing and building cryogenic space flight hardware is now being combined with the partnered resources of the government and Academia in the NCAM program to produce a facility with unmatched research, design, and production capabilities.